National Aeronautics and
Space Administration

ESMD-RQ-0014
Preliminary (Rev. A)
Effective Date: 22 Feb 2005

Exploration Systems Mission Directorate

National Aeronautics and Space Administration, Headquarters
Washington DC 20546-0001

Robotic Lunar Exploration Program Requirements Document

Preliminary Version – Revision A
22 Feb 2005

Document History Log

Status (Baseline/Revision/ Cancelled)	Document Revision	Effective Date	Description
Preliminary	**--**	**1 Sep 2004**	
Preliminary (Rev. A)	**Reviewer feedback**	**22 Feb 2005**	**LRO mission requirements moved to separate document**

Exploration System of Systems Technical Requirements Document

Submitted By:

Original Signed By:

Jennifer Trosper Robotics Requirements Lead Exploration Systems Mission Directorate	Date

Concurred by:

Original Signed By:

Michael F. Lembeck, PhD Director, Requirements Formulation Division Exploration Systems Mission Directorate	Date

Concurred by:

Original Signed By:

Tom Jasin, PhD Robotic Lunar Exploration Program Director Science Mission Directorate	Date

Concurred by:

Original Signed By:

Tom Morgan, PhD Robotic Lunar Exploration Program Scientist Science Mission Directorate	Date

Concurred by:

Jim Watzin Robotic Lunar Exploration Program Manager Goddard Space Flight Center (GSFC)	Date

Concurred by:

Jim Garvin, PhD Chief Mars and Moon Scientist NASA HQ	Date

Concurred by:

Terri Lomax, PhD Sr. Advisor, Research and Technology Exploration Systems Mission Directorate	Date

Concurred by:

Jim Nehman Director, Development Programs Division Exploration Systems Mission Directorate	Date

Concurred by:

John D. Baker
Lunar Robotic Program Coordinator
Exploration Systems Mission Directorate

Date

Concurred by:

Doug Cooke
Deputy Associate Administrator for Development Programs
Exploration Systems Mission Directorate

Date

Approved by:

Craig E. Steidle
Associate Administrator
for Exploration Systems

Date

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1 Introduction

1.1 Purpose

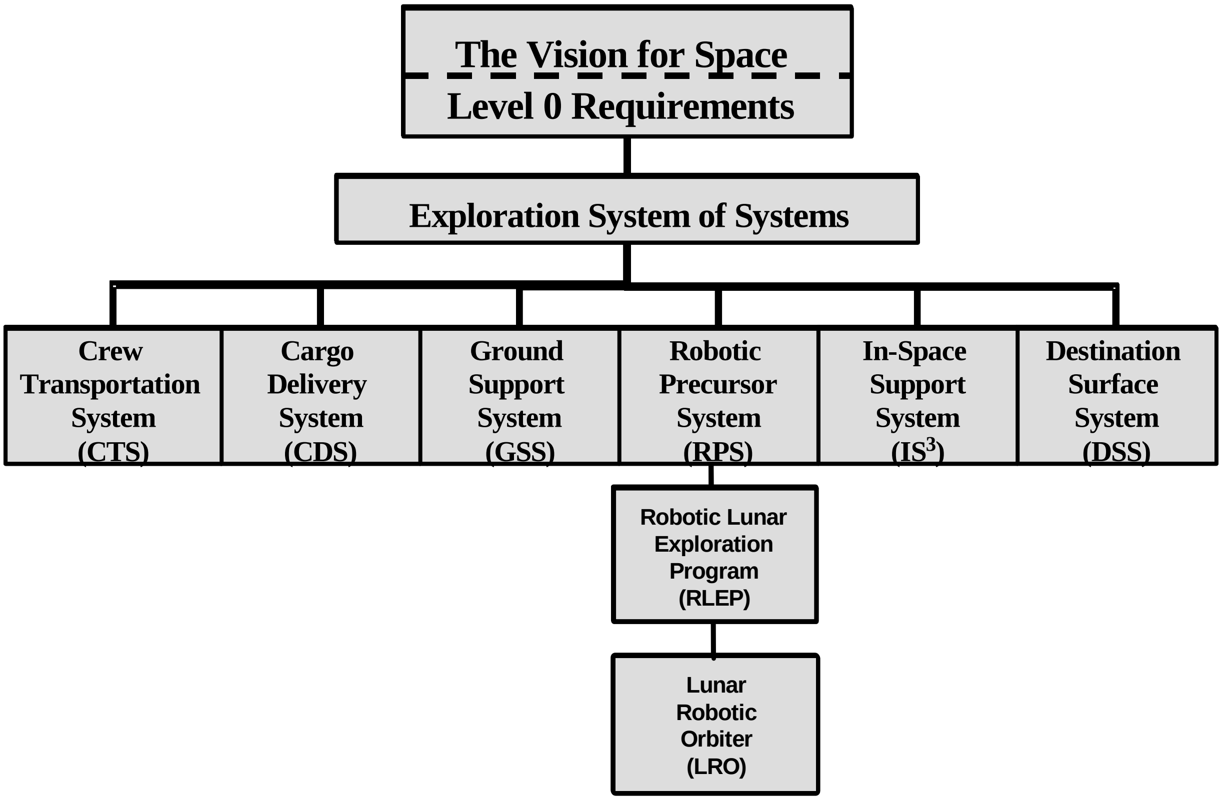
NASA's Vision for Space Exploration has the fundamental goal of advancing scientific, security, and economic interests through a robust space exploration program. The robotic missions to the Moon play a critical role in this vision. Starting in 2008, NASA will initiate a series of robotic missions to the Moon to ***prepare for and support future human exploration activities***. The primary purpose of the robotic preparation and support for human missions is to ***reduce risk, enhance mission success, and reduce cost of future human missions.*** This will be accomplished by designing and implementing a Lunar program of robotic missions to collect critical measurements, demonstrate key technologies and emplace essential infrastructure.

A secondary purpose of the robotic portion of the VSE is to enhance U.S. scientific, security, and economic interests by directly engaging the private sector, international partners, and the general public in robotic exploration of the Moon, Mars, and beyond.

1.2 Document Scope

This document provides the Robotic Lunar Exploration Program requirements. The Exploration Systems hierarchy shown in Figure 1 explains the hierarchy of requirements documents that flow down from The Vision.

Although several sections of this document include discussion of Lunar robotic precursor mission activities for extended duration operations (Exploration Spiral 2), long duration operations (Exploration Spiral 3), and sustained presence on the Moon, this revision of the document contains only the Lunar robotic precursor Spiral 1 requirements which are defined as those requirements necessary to support Exploration Spiral 2 (Global Lunar Access for Human Exploration). An update to this document will include the Robotic precursor Spiral 2 requirements which are defined as those requirements for support of Exploration Spiral 3 (Lunar Base and Mars Testbed).



1.3 Reference Documents

The documents that follow are referenced in the text of this document.

SA-0001, Level 0 Exploration Requirements for the National Aeronautics and Space Administration, Baseline Version, May 4, 2004

Objectives and Requirements Definition Team (ORDT) for the Lunar Reconnaissance Orbiter (LRO)

JSC 62577, Bioastronautics Critical Path Roadmap (BCPR)

Report of the President's Commission on Implementation of the United States Exploration Policy, A Journey to Inspire, Innovate, and Discover. June 2004

National Aeronautics and Space Administration, The Vision for Space Exploration. February 2004.

Mars Exploration Strategy 2009 - 2020, Mars Science Program Synthesis Group. 2002 - 2003.

Strategic Considerations for Support of Humans in Space and Moon/Mars Exploration Missions, NASA Advisory Council 1992.

NASA Conf. Publ. 3360, Shielding Strategies for Human Space Exploration, Dec. 1997

RFT0004.04, JSC Lunar Surface Crew Systems Technology Task

Science, Vol 281, issue 5382, 4 September 1998, Fluxes of Fast and Epithermal Neutrons from Lunar Prospector: Evidence for Water Ice at the Lunar Poles

Mars Exploration Program Analysis Group (MEPAG) Goals Document, 2004

ESA Publ. Div., Humex: Study on the Survivability and Adaptation of Humans to Long-Duration Exploratory Missions. European Space Agency. Noordwijk.

Advanced Integrated Matrix (AIM) Inter-divisional Team Dust Assessment, August 20, 2004.

Final Report, February 1995, Lunar Surface Exploration Strategy, Lunar Exploration Science Working Group (LExSWG)

NNH04ZSS003O, Announcement of Opportunity, Lunar Reconnaissance Orbiter (LRO) Measurement Investigations

Lunar Reconnaissance Orbiter (LRO) Payload Proposal Information Package (PIP)

NPR 7150, Software System Engineering Requirements

2 Approach

2.1 Team

The Lunar Architecture Working Group (LAWG) Team began meeting May 27, 2004. The team consists of the lead engineers from the Goddard Robotic Lunar Exploration Program (RLEP) Science Mission Directorate (SMD) office as well as Exploration Systems Mission Directorate (ESMD) requirements, development, research and technology representatives. The team members and authors of this report are listed in Table 1. Additional support from Rich Vondrak (HQ RLEP Program Office), James Watzin (GSFC RLEP Program Office), and Orlando Figueroa (HQ SMD DAA) was valuable to the development of the requirements.

Name	Organization	Title
John Baker	HQ ESMD	Lunar Program Coordinator
Joe Burt	GSFC	RLEP Future Programs Lead
John Connolly	HQ ESMD	Constellation Development
Carmel Conaty	HQ ESMD	Research and Technology Representative
Jim Garvin	HQ SMD	NASA Chief Scientist
Martin Houghton	GSFC	RLEP Future Mission Design Lead
Terri Lomax	HQ ESMD	Senior Research and Technology Advisor
George Tahu	HQ SMD	Mars and Lunar Program Office Representative
Jennifer Trosper	HQ ESMD	Robotics Requirements Lead

TABLE 1 LAWG Requirements Formulation Team

2.2 Process

The roadmap for turning the Vision for Space Exploration into deliverable products is through implementation of a Strategy-to-Task-to-Technology (STT) process. Strategy-to-Task-to-Technology is a top down process whereby high level goals and objectives flow down to lower level requirements and systems. Through this process, simulation and analysis capabilities are used to model system concepts interacting in their operational environments to identify necessary performance capabilities. These capabilities are assessed to determine any technology gaps. Then, working with technologists, a technology/capability investment plan can be formulated to close the capabilities gaps over time, re-evaluate the resulting system using Figures-of-Merit (FOM), and in an iterative fashion obtain an affordable and sustainable system architecture and component element designs for implementing the Vision.

The focus of the LAWG has been to identify a robotic Lunar exploration program that directly supports the Vision for Space Exploration by flowing down the high level vision goals to a set of NASA Agency -level objectives associated with exploration. These are then analyzed and flowed down to a set of RLEP requirements. This process was accomplished by evaluating several past studies and reports which are listed in the Reference Document Section. These reports and analyses provided essential data to understand the measurements, technologies, and infrastructures necessary to prepare for and support future human missions.

A key tool used in the Strategy-to-Task-to-Technology process is the identification and management of Key Performance Parameters (KPPs). As the program requirements are further flowed down to the Mission-Specific Level 1 requirements, the KPPs for each mission will be identified. Future work and studies are still required to refine the requirements in this document.

2.3 Strategy

The primary activities necessary to prepare for and support human missions were identified as part of the STT process and are shown in Figure 1.

The strategy for determining the priority and timing of these activities was derived from the objective to prepare for and support future human exploration and from the high level objective to provide a sustainable, affordable, and flexible program of exploration.

In order to determine capability priorities, FOMs were developed for the Lunar robotic precursor missions associated with the potential cost and risk reduction to future human missions. Each proposed program capability was evaluated in terms of its ability to reduce cost or risk and has been prioritized accordingly.

As a result of this process, a set of robotic precursor activities has been identified in preparation for the first human Lunar extended mission (Exploration Spiral 1 RLEP Requirements). Additional requirements for support of longer duration human missions to the Moon will be developed and delivered in updates to this document.

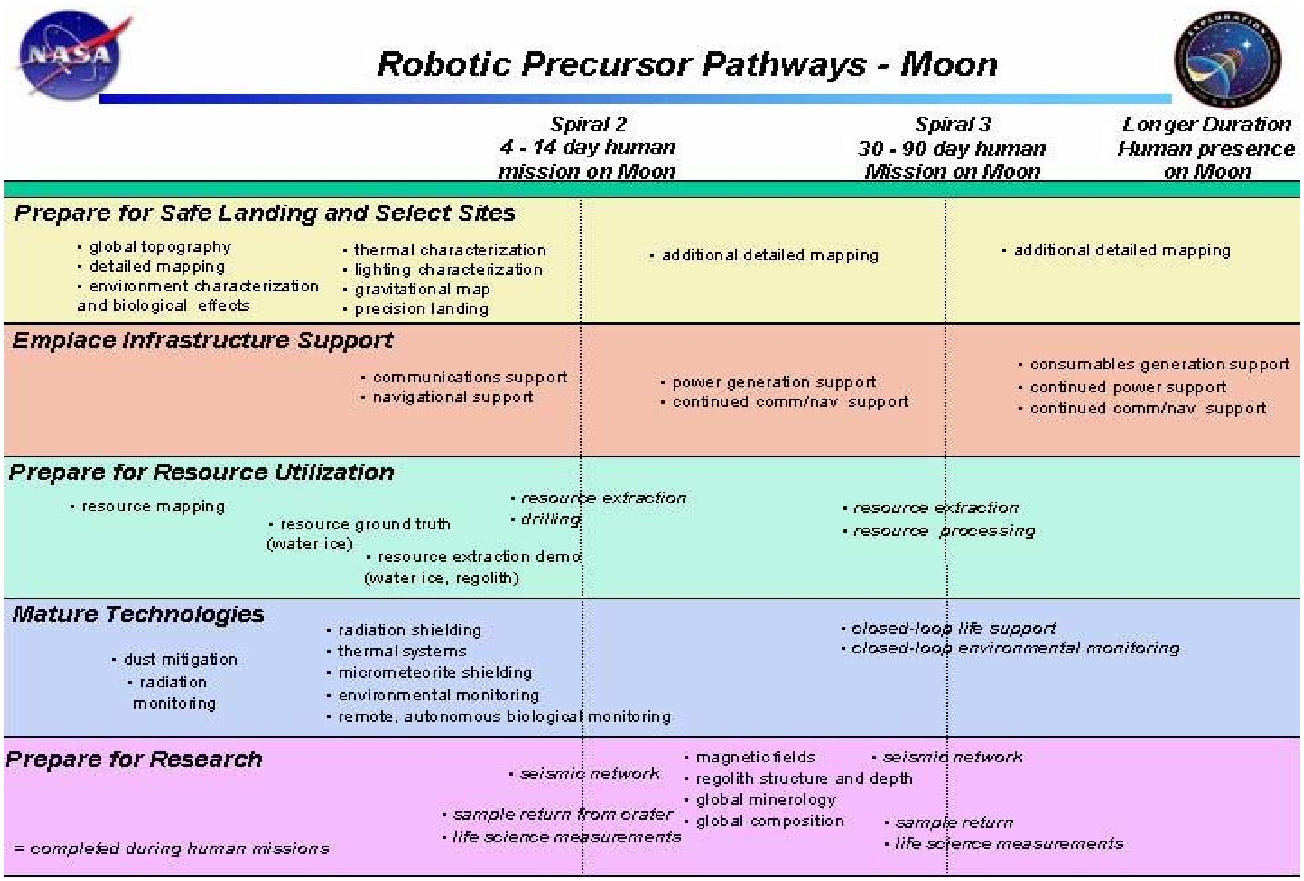


FIGURE 1 NOTIONAL TIMELINE OF LUNAR ROBOTIC PRECURSOR ACTIVITIES

3 Deliverables

3.1 RLEP Overview and Objectives

The STT process identified the 5 high level capabilities shown in Figure 1 as the primary objectives of the RLEP program. These objectives are: preparing for safe landing and selecting exploration-relevant sites, emplacing infrastructure support, preparing for and assessing the possibility of resource utilization, maturing technologies, and preparing for human-based *in-situ* science activities. The activities will be accomplished through executing a set of robotic precursor missions to the Moon.

The most important and fundamental of the activities the precursors perform is that of preparing for a safe landing and exploration-relevant site selection for the human missions. The activities required to prepare for an extended duration mission on the surface of the Moon (Exploration Spiral 2) relate primarily to global geodetic topography and detailed hazard-scale mapping for site selection and safe landing. There are also key environmental characteristics that must be understood for risk reduction to human missions as well as robotic and human vehicle design. The radiation, thermal, and lighting environments are the items of primary interest in preparation for a short stay on the Moon. Of particular interest for mapping and environmental characterization are the Lunar polar regions where there is potential for water ice resources to be located in some of the shadowed regions, or in shallow, accessible subsurface.

As the precursors prepare for potentially longer duration missions to other sites on the Lunar surface, additional topographic and resource-relevant mapping will be required for site selection and landing safety.

Providing support for the human missions with preparatory and/or coincident placement of communications/navigation, power, and other necessary infrastructure is also a fundamental objective of the precursors. In preparation for Spiral 2, support for communications during the critical portion of the human mission during the landing on the surface at a high priority site, such as that afforded by the Lunar south polar region may be required. As the human missions grow in duration, additional support such as power and additional communications emplacement may be necessary. Eventually, if it is determined that humans must stay for a long time on the surface of the Moon in order to enable future human exploration of Mars, it's possible that infrastructure for resource extraction and generation would also need to be provided.

A third and important aspect of the precursors is the search for resources on the surface of the Moon. Currently, the resource of most interest is the potential for water ice at the Lunar poles. Lunar robotic precursors will use both orbital and *in-situ* ground truth data to determine whether this water ice actually exists and in what abundance. They must also determine the accessibility as well as the abundance of the resources. If found, technology demonstrations would be required to validate techniques for extraction of water ice from the Lunar surface materials within which it resides. Also of interest, is the oxygen in the Lunar regolith and surface rocks. Technology demonstrations for small scale extraction of O_2 could be accomplished as part of Spiral 2. Once the humans land on the surface, additional surveying for resources and resource extraction (such as drilling) will be completed as part of the human missions. Longer duration stays on the surface will possibly lead to requirements for larger scale resource extraction and processing if it is determined that this is economically beneficial. In situ resource extraction at the poles also requires the creation and installation of infrastructure for conveying electric power from the conversion site to the consumption site.

Technology maturation is also a critical component of the robotic precursor missions. Through the STT process, a set of critical technologies can be prioritized for investment and when available, can be demonstrated as part of the Lunar robotic precursor program if necessary. The early technology demonstrations in RLEP include radiation and micrometeorite shielding assessment of materials with low mass atomic constituents that may be used for future missions. Critical components of human environmental monitoring systems can also be tested as a greater understanding of the Lunar environment is acquired. It is also expected that precision landing technologies will be required for safe landings of the precursory robotic missions as well as ensuring that all missions land in the desired locations. Additional technology demonstrations such as dust mitigation will aid in robotic vehicle design and in Extravehicular Activity (EVA) suit design for humans and demonstration of thermal systems will aid in the design of vehicles in extreme thermal environments.

Finally, a very important aspect of the precursor requirements is preparing for and supporting the highest priority research to be performed by the human missions on the Moon. This will involve cooperative work between humans and robots during the landed missions to perform key research activities such as life science experiments, highly informed sample selections (including subsurface), and other detailed investigations of the surface and interior of the Moon. As we move from Spiral 2 on to future Spirals, additional mapping of the surface should be completed to determine other desirable landing sites for research investigations on the Lunar surface.

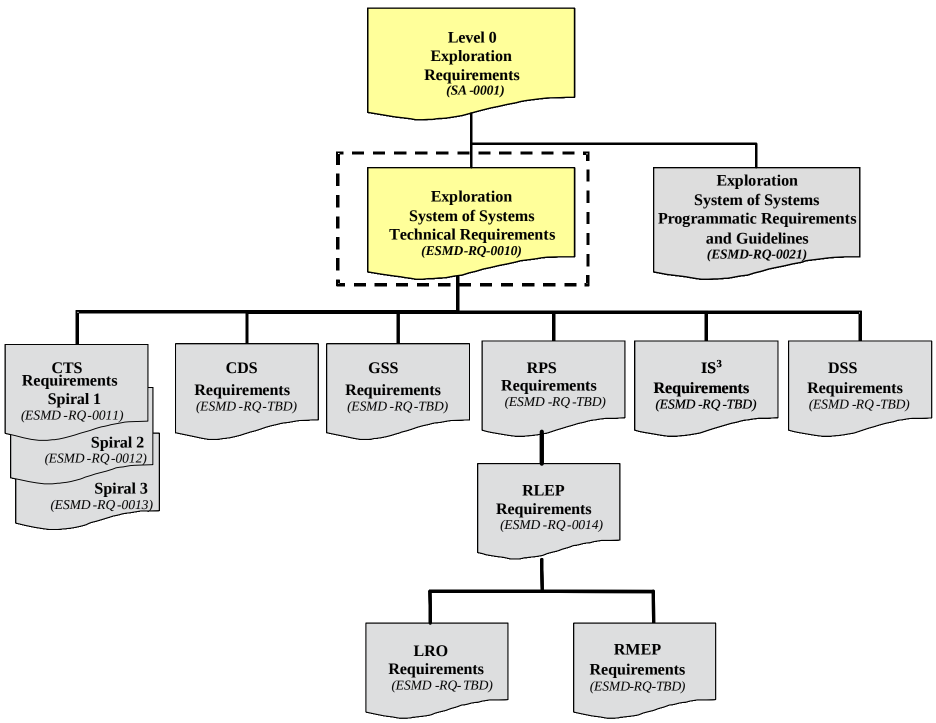


FIGURE 2 RLEP REQUIREMENTS FLOW-DOWN AND TRACEABILITY

3.2 RLEP Level-0 and Level-1 Requirements Flow-down and Traceability

The RLEP Requirements flow-down is shown in Figure 2. The Exploration Level 0 Requirements were derived from the Vision for Space Exploration, February 2004. Exploration Systems of Systems (ESS) requirements were generated which flow-down to the Robotic Precursor System requirements. These Robotic Precursor System requirements include both Lunar and Mars Program requirements. Program requirements include the full set of required capabilities across a set of missions. Individual Mission Requirements are derived from these Program requirements through an identification and analysis of alternate architectures for supporting the program requirements. Once an architecture of missions is selected, the Mission specific requirements are written. The relevant RLEP requirements documents and flow are highlighted in yellow.

A listing of key applicable Level-0 Exploration, Constellation, and Robotic Precursor System requirements and objectives are shown below in Table 2.

Exploration Level 0 Requirements and Level 1 Objectives Relevant to RLEP		
(1)		NASA shall implement a safe, sustained, and affordable robotic and human program to explore and extend human presence across the solar system and beyond.
	1.1	NASA shall develop the innovative technologies, knowledge, capabilities, and infrastructures to support human and robotic exploration
	1.2	NASA shall conduct a series of robotic missions to the Moon to prepare for and support future human exploration activities
(1)		NASA shall develop and demonstrate power generation, propulsion, life support, and other key capabilities required to support more distant, more capable and/or longer duration human and robotic exploration of Mars and other destinations.
	(1.1)	Starting no later than 2008, NASA shall initiate a series of robotic missions to the Moon to prepare for and support future human exploration activities.
	(1.2)	NASA shall conduct the first extended human expedition to the Lunar surface as early as 2015, but no later than the year 2020, in preparation for human exploration of Mars and other destinations.
(4)		NASA shall pursue opportunities for international participation to support U.S. space exploration goals.
(5)		NASA shall pursue commercial opportunities for providing transportation and other services supporting the International Space Station and exploration missions beyond low earth orbit.
(6)		NASA shall identify and implement opportunities within missions for the specific purposes of inspiring the Nation.
ESS Spiral 1 and Robotic Precursor System Requirements Relevant to RLEP		
ESS0010		The Exploration Super-System shall conduct robotic exploration of the Moon using established safety requirements and processes for development and operations.
ESS0070		The Exploration Super-System shall demonstrate power generation, propulsion, life support, and other key capabilities required to support human and robotic exploration of Mars and other destinations.
ESS0090		The Exploration Super-System shall provide information, data, and scientific opportunities to support public and educational outreach activities.
ESS0110		The Exploration Super-System shall conduct robotic precursor missions to lunar orbit and lunar surface to prepare for future human exploration.

TABLE 2 RELEVANT REQUIREMENTS FOR RLEP

3.3 RLEP Spiral 1 Requirements Structure and Definition

The following Robotic Lunar Exploration Program Spiral 1 Requirements and Guidelines have been identified in support of the extended duration (Spiral 2) human mission to the Moon.

3.3.1 Programmatic Requirements

RLEP-P10 The RLEP shall design and implement a series of missions between 2008 and 2015 that prepare for and support the first human mission to the Moon in the 2015-2020 time period.

Rationale : The Level 1 Exploration Objectives indicate in Objective 1.1 the starting date for the first robotic mission to the Moon of 2008. In addition, the Level 1 Exploration Objectives states, “NASA shall conduct the first extended human expedition to the Lunar surface as early as 2015, but not later than the year 2020, in preparation for human exploration of Mars and other destinations.” In order to have executed the required robotic preparation and support activities for the first human mission, the initial phase of the RLEP activities must be completed by the 2015 - 2020 time period.

RLEP-P20 The RLEP shall allow for continuing program architecture flexibility to accommodate new measurement data, research findings, and exploration program architectural changes into subsequent mission planning.

Rationale : The Vision for Space Exploration identifies robustness as a key component to sustainable exploration, from which is derived a need to be flexibleThe incorporation of flexibility into the robotic Lunar program architecture will allow for discoveries along the way to influence future missions and plans. As measurement and technology demonstration data are acquired, the possible discoveries (i.e. water ice at the pole) will feed into the future plans for both the robotic and human mission architectures. In addition, technology advances and human architectural changes will occur and potentially affect the robotic Lunar program objectives. The Mars Exploration Strategy Report from the Mars Science Program Synthesis Group identifies flexibility to accommodate future scientific discoveries as an essential aspect to a program of discovery.

RLEP-P30 The RLEP shall design and implement a program with resiliency to mission failures.

Rationale : The Vision for Space Exploration indicates the need to design and implement a sustainable program for space exploration. In order to achieve sustainability, the program must be designed with a program level “graceful degradation” philosophy in which the failure of one mission does not preclude or significantly delay meeting future objectives in the program.

RLEP-P40 The RLEP shall archive all RLEP mission data and higher level data products in suitably calibrated and validated form and deliver them to ESMD and the Planetary Data System (PDS) consistent with the project data management plans.

Rationale : The Exploration Level 0 requirements identified earlier indicate that the purpose of the Lunar robotic missions to prepare for and support human exploration activities. This feed-forward aspect of the Lunar robotic program requires discipline in acquiring the mission level data and creating and making available the higher level data products for use by the future robotic and human missions that require this data. Each project’s data management plan will indicate the timeliness and content of the required data products.

RLEP-P50 The RLEP data shall have no proprietary data rights.

Rationale : Data from the RLEP missions has valuable feed-forward aspects to future missions and it is essential that proprietary data rights do not preclude the necessary data from being available or cause unnecessary obstacles in its usage.

RLEP-P60 The RLEP shall plan, implement, and budget an extensive public engagement program for the Lunar robotic missions.

Rationale : The Level 0 Exploration Requirements state "NASA shall identify and implement opportunities within mission for the specific purposes of inspiring the Nation." The RLEP missions to the Moon will be an opportunity for the public to participate in exploration and its benefits.

RLEP-P70 The RLEP shall develop and execute a Robotic Lunar Exploration Program Plan.

Rationale : A program plan is required to ensure the details associated with the successful execution of the program including budget, schedules and review plans have been documented and are understood both by SMD, participating centers and ESMD.

RLEP-P80 The RLEP shall develop and execute a Robotic Lunar Exploration Program Acquisition Strategy.

Rationale : A program acquisition strategy is essential for understanding the timelines for mission development and implementation as well as the competitive aspects of the acquisition plan. It is essential that this strategy be documented and understood by SMD, participating centers, and ESMD.

RLEP-P90 The RLEP shall perform program architecture and mission trade analysis to validate program architectural and mission plans in support of ESMD.

Rationale : Analysis of alternative architectures and mission level trade studies is essential to understanding how best to meet the requirements to reduce risk and cost and enhance the overall performance of the future human missions. These analyses will be used by ESMD to specify program and mission requirements.

RLEP-P100 The RLEP System shall comply with NPR 7150, NASA Software Engineering Requirements.

Rationale : NPRs are agency level requirements and not at the discretion of the Directorate. Specific version and dates shall be identified in the spiral requirements.

3.3.2 Programmatic Guidelines

RLEP-PG10 The RLEP should leverage other Lunar missions within and outside of NASA for meeting the RLEP requirements and should allow for international participation consistent with ESMD international strategy and resulting international agreements.

Rationale : The Vision for Space Exploration indicates that the alignment of ongoing programs with the Exploration Vision is an important aspect of sustainable exploration. Furthermore, the Level 0 Exploration Requirements state "NASA will pursue opportunities for international participation to support U.S. space exploration goals." In particular for the Moon, there are several missions within and outside of NASA that may be synergistic with the objectives and requirements of the Lunar exploration program. Although it is understood that not all opportunities will be able to be realized in this area, it is essential to review and analyze the current mission set to the Moon and understand the possible enhancements to, synergies with and /or modifications to RLEP that may result. In addition, receiving data from these missions may be a way to reduce cost to the RLEP program as a whole.

RLEP-PG20 The RLEP should promote commercial participation as much as practical in the development and execution of the RLEP missions.

Rationale : The President's Commission on the Implementation of the United States Space Exploration Policy states: "Our goal is to transform space exploration from a small, experimental research program, largely performed under the auspices of government into a fully integrated sector of American life, involving government, commercial, educational, and industrial players." The participation of these communities in RLEP is enabling to the development of this robust space industry identified in the President's Commission report.

RLEP-PG30 The RLEP should strive to establish as much as possible interoperable communications with all ESS systems and other NASA internal and external Lunar missions where it would be advantageous to the exploration effort.

Rationale : The Vision for Space Exploration indicates that the alignment of ongoing programs with the exploration vision is an important aspect of sustainable exploration. For example, the risk and cost reduction associated with the communications interoperability of vehicles in the vicinity of Mars has been demonstrated through the Mars Exploration program. The architectural robustness provided by interoperable communications on Lunar vehicles will be valuable to the RLEP program.

3.3.3 Measurement Requirements

RLEP-M10 The RLEP shall acquire measurements of the biologically relevant radiation environments, in particular the radiation albedo, in Lunar orbit and on the Lunar surface in the polar regions.

Rationale : The heavy nuclei in the galactic cosmic rays (GCRs) and the many secondary particles, especially neutrons, that GCRs generate in the Lunar soil are a hazard to humans and sensitive electronic equipment on the Moon. The 2008 Lunar Recon Orbiter Objectives/Requirements Definition Team (ORDT) listed radiation characterization of the moon as a high priority measurement specifically the neutron albedo (in particular energies in excess of 10 MeV which are more damaging to humans). The report, Strategic Considerations for Support of Humans in Space and Moon/Mars Exploration Missions, NASA Advisory Council (1992) recommended characterization of deep space radiation environments and the determination of human radiation dose limits for space missions (protons and galactic cosmic radiation). In order to set dose limits, increased knowledge of both the radiation environment and biological responses to that environment are required. The characterization of the orbital and polar surface radiation environments will allow for proper mitigations to be developed to reduce risk for future mission to the Moon which may land in the polar regions.

RLEP-M20 The RLEP shall investigate the potential biological impacts of the combined Lunar environments including radiation, partial gravity, thermal, micrometeorites, and dust. The capability to perform experiments in space or on the Lunar surface shall include remote autonomous experiments and statistically meaningful sample sizes.

Rationale : Investigation of the biological impacts of the Lunar environment was identified as a measurement for the purpose of reducing risk to crew safety during the human missions to the Moon. The ORDT identified the characterization of the global Lunar radiation environment and its biological impacts as a primary objective of the Lunar robotic precursors. Health risks from radiation identified by the Bioastronautics Critical Path Roadmap report include; carcinogenesis, acute and late central nervous system damage, tissue degeneration, fertility and sterility impacts and acute radiation syndromes. Most data on human responses to radiation come from studies of atomic bomb and nuclear accident survivors. These people suffered acute exposure to high-flux gamma rays, rather than chronic or fractionated exposure to the low-flux protons or heavy ions that astronauts are more likely to encounter. Currently, the effects of space radiation on humans must be extrapolated from data on humans exposed to other types of radiation or animals exposed to space-like radiation. The Moon affords a good opportunity to advance our understanding of radiation effects on humans as well as study the interactive effects of partial gravity, radiation, dust and thermal conditions on organisms, including humans. Early applied robotic studies on small organisms may provide knowledge critical for validation of risk models that will be used for projecting human health risks and performance degradation and influence mission design requirements (e.g. shielding, operational mandates, and countermeasure development). This approach will result in significant risk mitigation for human Moon and Mars exploration missions.

RLEP-M30 The RLEP shall perform measurements to acquire a high spatial resolution global center of mass referenced (geodetic) grid for the Moon in 3 dimensions.

Rationale : The establishment of a high spatial resolution geodetic grid for the Moon was identified as a key measurement for the purpose of reducing risk to human landings on the Moon by the ORDT. Specifically, the ORDT recommended "determining global geodetic knowledge by means of spatially resolved topography and performing detailed topographic characterization at landing-site scales". Global geodetic knowledge (spatially resolved topography) is required to tie inertial coordinates to actual surface features at landing site scales. Establishing the geodetic grid enables detailed topographic characterization at landing site scales. This is especially important in polar regions where resolving topography is required to determine lighting and thermal conditions at the permanently shadowed craters. It is also important for establishing safe descent and landing activities. For human performance, it may be important for the crews to have daily periods of dark and light (circadian rhythm issues). There is also the potential for significant cost savings of crew habitat designs if ambient light can be used instead of artificial light.

RLEP-M40 The RLEP shall perform imaging of selected sites at landform scales as well as landing site scales relevant to hazards.

Rationale : Imaging of selected sites was identified as a measurement that will reduce the risk to both robotic and human landings on the surface of the Moon. Several studies including the ORDT concluded that stereo imaging at ?1 meter resolution is necessary to provide mission planning data in terms of terrain analysis and for mobility and safe landing operations. The ORDT also recommended landform scale imaging. With these measurements, site characterization and selection for future robotic and human missions to the surface of the Moon is enabled.

RLEP-M50 The RLEP shall acquire orbital and *in-situ* ground truth measurements for identification of potential H_20 ice resources and other volatiles on or below the Lunar surface.

Rationale : The search for resources on the Moon is indicated in the Vision for Space Exploration as an activity that will be performed on Mars and other destinations. Lunar Prospector identified potential signs of water ice at the poles as discussed in the Science Magazine report, "Fluxes of Fast and Epithermal Neutrons from Lunar Prospector: Evidence for Water Ice at the Lunar Poles". The ORDT identified the "assessment of resources in the Moons polar regions, including permanently shadowed regions and evaluation of any water ice deposits" as a high priority Lunar program activity. In addition, identification of H_20 ice resources on the Moon, could lead to future cost reduction of Lunar human missions through the use of these resources to supply the crews while on the Lunar surface through *in-situ* resource utilization (ISRU). Several NASA studies including JSC study RFT0004.04 indicate the need to investigate potential ISRU on the Lunar surface for support for future human missions. Practice for Mars includes methods and instrumentation for identifying water via remote robotic vehicles both in orbit and on the surface.

RLEP-M60 The RLEP shall acquire orbital and *in-situ* ground truth measurements of the thermal environment of the polar regions for a full Lunar day.

Rationale : Characterization of the thermal environment in the polar regions was identified as a measurement that would reduce the risk of future human mission thermal designs and potentially help in the identification of cold-traps capable of preserving small amounts of Lunar water ice. The ORDT identified "Temperature mapping in polar shadowed regions" as a high priority measurement for the Lunar program. Orbital data will produce high-resolution topographic maps of the Lunar polar regions, and geodetic data will allow this data to be used in constructing an accurate model of the Moon that can be used for detailed lighting and thermal modeling. Orbital and ground truth data of actual conditions will be required to populate and validate these models, which will in turn identify possible locations of resources held in polar cold traps and aid in the thermal design of future mission.

RLEP-M70 The RLEP shall measure the radiation shielding capabilities of *in-situ* materials at the Moon.

Rationale : The measurement of radiation shielding capabilities was identified as a high priority measurement for the purpose of reducing risk to crew health on future human missions as well as potentially reducing cost by utilizing *in-situ* resources for radiation shielding. The ORDT identified measuring radiation shielding properties of materials as one of the top priority measurement sets. Many reports including Shielding Strategies for Human Space Exploration and others (NASA Conf. Publ. 3360, Dec. 1997, Science Vol 281 Sept 4 1998 page 1496).) have recommended the use of *in-situ* surface regolith as a readily available shielding material, but the actual radiation shielding properties of regolith need to be quantified, and will drive the design of surface habitation systems. The backscatter effects of the regolith need to be understood in order to validate radiation transport models. As the radiation shielding capabilities of the Lunar regolith are better understood, the proper usage of this regolith can be accurately incorporated into the human mission designs.

RLEP-M80 The RLEP shall acquire orbital and ground truth measurements for characterization of regolith [composition, mineralogy, structure] on the Lunar surface. [TBR-10]

Rationale : The search for resources on the moon is indicated in the Vision for Space exploration and is an activity that will be performed for Mars, the Moon, and other destinations. As a result, measurements for the purpose of characterization of the composition of the Lunar regolith and rocks are important because they will influence the type of *in-situ* resource utilization (ISRU) demonstrations that are attempted as part of the initial phase of RLEP. (i.e. to extract O2 for breathing). Several NASA studies including the Lunar Surface Exploration Strategy Lunar Exploration Science Working Group (LExSWG) Report, February 1995, indicate the use of oxygen from the Lunar regolith for ISRU is a valuable demonstration to pursue. Additional analysis is required to determine the regolith measurements necessary in order to prepare for the desired ISRU regolith technology demonstration. This initial analysis will be completed as part of the Lunar Exploration Program Working Group (LEPAG).

TBR-10 Closure Plan: The characterization of regolith will be defined prior to SRR.

RLEP-M90 The initial phase of RLEP shall improve the global gravitational map of the moon by incorporating far side gravity measurements.

Rationale : An improved far-side gravity model will allow for low altitude orbital missions which potentially require less propellant and less Deep Space Network (DSN) tracking. In addition, the improved gravity models will assist in lowering the gravity model induced errors relative to precision landing on the surface from Lunar orbit. Therefore, this measurement will potentially reduce both cost and risk to future missions

3.3.4 Technology Requirements

RLEP-T10 The RLEP shall demonstrate precision landing on the Lunar surface.

Rationale : The demonstration of precision landing was identified as a key technology to mature for the purpose of reducing landing risk to future human missions. The Mars Exploration Program Analysis Group (MEPAG) approved 2004 MEPAG Goals document identifies precision landing as a key technology in the objectives in preparing for human exploration at Mars. Supporting studies identify the types of activities precision landing would enable for Lunar and Martian missions. This technology enables concepts of operations at the Moon and Mars where missions will be targeted to specific landing locations on the surface. Targeting to specific locations is necessary for the search and identification of resources, focused science, and emplacement of infrastructure such as power systems in specific locations with appropriate shielding. In addition, there may be requirements to return more than once to landing locations in order to establish a reliable human surface presence on the Lunar surface.

RLEP-T20 The RLEP shall demonstrate prototype systems used for monitoring Lunar environmental effects on humans including radiation, partial gravity, dust and thermal effects.

Rationale : Technology maturation is one of the key objectives of the RLEP program consistent with Level 1 Exploration Objective (1.1). The Bioastronautics Critical Path Roadmap (BCPR) states “missions of greater duration and distance require human support technologies that are more autonomous, efficient and reliable. Such technologies must function under variable gravity conditions, guarantee crew health and safety and enable optimal performance throughout the mission.” A reliable, validated system that can be used repeatedly will significantly lower cost and risk. It is recommended first system be available for solar max in 2011.

In particular for radiation, current detectors on International Space Station (ISS) haven’t measured the higher energies (up to 200 MeV) and have not proven reliable. The deep space radiation prototype hardware is needed to validate existing calculations/models for Lunar environment. Validation needs to be performed outside Earth's magnetosphere (ISS is not an acceptable validation), however this validation could be done by either an orbiter or a lander. Additional recommendations from *Humex: Study on the Survivability and Adaptation of Humans to Long-Duration Exploratory Missions. European Space Agency. Noordwijk: ESA Publications Division. 2003* include:

- Improve solar monitoring, modeling in order to better predict SPEs
- Find ways in which instruments that are used can remain functional without the possibility of support from Earth
- Design passive detector stacks to measure the accumulated dose of heavy ions that can survive flight and are sensitive to the correct spectrum of particles.

For thermal effects, lunar surface temperatures increase about 280K from just before Lunar dawn to Lunar noon, with the temperature at Lunar noon varying throughout the year. An accurate thermal monitoring system will be needed to enable the efficiency and effectiveness of the astronaut suits.

RLEP-T30 The RLEP shall validate prototype systems used for mitigating (including shielding) space environment effects on humans and systems including radiation, partial gravity, dust and thermal effects.

Rationale : An essential cost and risk reducing activity for robotic precursor missions was identified by the (former) Code U workshop analysis group for Lunar Missions as validating prototype systems used for mitigating space environment effects on humans and systems.

In particular for radiation, recommendations by the National Academy of Science, the National Council on Radiation Protection and Measurements, and the radiation protection community have remained constant since 1970 and include using new radiobiology knowledge and data to develop optimal shielding approaches The ORDT recommended measuring the radiation shielding properties of materials as part of their top priority measurement set. Measurements of the performance of imported radiation materials must be performed and radiation transport models calibrated for each shielding option.

Apollo astronauts were exposed to Lunar dust which was inhaled and it also irritated their eyes. The Dust Assessment Report states that the effects of Lunar dust must be well understood to protect the crew in the Lunar environment.

According to the Bioastronautics Critical Path Roadmap, when astronauts adapt to a Moon gravitational environment, balance, locomotion and eye-head coordination are transiently disrupted. In addition, during a gravitational transition, head movements and/or vehicle maneuvering can cause spatial disorientation, perceptual illusions and/or vertigo. Monitoring of the gravity especially during transitions is critical to the mitigation of these effects.

RLEP-T40 The RLEP shall demonstrate *in-situ* resource utilization (ISRU) of Lunar water ice if any is observed in sufficient quantities.

Rationale : The vision for Space Exploration indicates experimentation should be completed to understand the possibilities of utilizing relevant *in-situ* resources for future exploration activities. The MEPAG Goals document identified the demonstration of *in-situ* water ice collection and conditioning using surface resources as a high priority investigation. In addition, several NASA studies including RFT0004.04 JSC Lunar Surface Crew Systems Technology, indicate the extraction of water is of special interest because it possibly exists on both the Moon and is known to exist on Mars. This experimental verification of ISRU for *in-situ* water ice will reduce the risk and cost of the human exploration of Mars and potentially reduce the cost of the Lunar missions as well.

RLEP-T50 The RLEP shall demonstrate thermal management technologies and assess their performance on the Lunar surface.

Rationale : Providing light-weight thermal heat rejection capability for the Lunar and Martian surfaces conducive to surface environments such as dust and temperature extremes is necessary according to several NASA studies including RFT0004.04 JSC Lunar Surface Crew Systems Technology. Designs which minimize sensitivity to leveling of radiators and maximize emmissivity while minimizing mass will provide useful feed-forward data to the human mission thermal designs.

RLEP-T60 The RLEP shall demonstrate power technologies and assess their performance on the Lunar surface.

Rationale : Technology advances are required in support of future human exploration missions according to the Lunar Surface Exploration Strategy Lunar Exploration Science Working Group (LExSWG). The areas of interest include in-space and stationary surface power generation, mobile power for rovers, energy storage, and power distribution systems. To enable robust exploration in near-Earth space and beyond, advances in each phase will be required." Demonstration of advanced power system technologies will be useful TRL advancement and feed-forward to the human program.

RLEP-T70 The RLEP shall determine environmental effects on systems, in particular of Lunar dust on life support systems.

Rationale : The Level 0 Requirement (1.1) requires the development of innovative technologies, knowledge, capabilities, and infrastructures to support human and robotic exploration. Assessment of the Lunar environmental effects on systems is an essential aspect of this development. The Advanced Integrated Matrix (AIM) Inter-divisional Team Dust Assessment, August 20, 2004, states that planetary dust leads to major system and mission failure risks. This study cited the problems with Lunar dust contamination on Extra Vehicular Activity (EVA) suit bearings and with dust transported in the Lunar Module affecting crews. The top two risks identified by that study were the risk of critical life-safety systems failing due to dust build-up on systems and the risk that the if the crew inhales or ingests dust adverse health effects will result. Systems do not currently exist to function on the Lunar dusty environment. Understanding how to shield filters, pumps, materials, seals, etc., is essential to driving the design of life support components that will be exposed to and may be affected by fine Lunar dust. Dust contamination is viewed as a significant issue in regards to the habitat and EVA systems, and the introduction of dust into the breathing volume. Techniques that remove dust or limit dust brought into the breathing volume should be investigated.

RLEP-T80 The initial phase of RLEP shall demonstrate systems that may be affected by partial gravity including (ISRU, In Situ Fabrication and Repair, Advanced Life Support and Advanced Environmental Monitoring and Control components).

Rationale : Multi-phase flow in partial gravity needs to be understood to ensure that all components that utilize a liquid-vapor or liquid-gas system behave in a predictable manner. The National Research Council Study, Microgravity Research In Support of Technologies for the Human Exploration of Space and Planetary Bodies, 2000, identifies this as a high priority because the validated engineering data currently does not exist to adequately design these systems.

RLEP-T90 The RLEP shall demonstrate *in-situ* resource utilization (ISRU) of Lunar regolith.

Rationale : The Vision for Space Exploration indicates experimentation should be completed to understand the possibilities of utilizing resources for future exploration activities. Several NASA studies including The Lunar Surface Exploration Strategy, Lunar Exploration Science Working Group (LExSWG) Report, June 1995, indicate the benefits of demonstration and potential usage of Lunar regolith ISRU on the surface. The Apollo and Surveyor Lunar missions determined that the Lunar regolith is nearly 50% oxygen. Utilization of this oxygen for support of human missions could potentially reduce the cost and mass of those missions.

RLEP-T100 The RLEP shall demonstrate additional key technologies identified by ESMD. [TBR-12]

Rationale : Additional analysis is required to determine other critical technologies that require demonstration as part of the Lunar robotic precursor program. This analysis will include an evaluation of the HR&T and INSTEP programs to identify required robotic precursor technology demonstrations. An initial version of this analysis is required for the Lunar Program Architecture alternatives studies.

TBR-12 Closure Plan: Additional key technologies will be defined prior to SRR.

3.3.5 Infrastructure Requirements:

RLEP-IN10 The RLEP shall provide interoperable communications support for ESS systems.

Rationale : Although the primary communication for Constellation will be provided by the Constellation program, interoperable communications assets between RLEP assets and Constellation assets for program resiliency and back-up purposes.

RLEP-IN20 The RLEP shall utilize communications assets that are evolvable as the program matures.

Rationale : This requirement establishes program robustness, resiliency and evolvability. As we continue to send both robotic and human spacecraft to the Moon, it is essential that we try to maximize the intercommunicability among assets. This is only possible if the current assets at the Moon can evolve to be compatible with future missions. Also, as has been learned through the Mars communications architecture, the vehicle lifetimes and successes vary over the course of a decade long program. The evolvability of systems on s/c emplaced earlier in the program will enable possible usage later thus potentially reducing both cost and risk to the program.

RLEP-IN30 The RLEP shall emplace additional infrastructure in the Lunar vicinity as well as on the Lunar surface in support of human and other robotic exploration.

Rationale : The Exploration Level 0 Requirements (1.1) and (1.2) require infrastructure development and support for human missions. Examples of potential infrastructure emplacement are communications, power, ISRU, and navigation. The [TBR] will be closed as part an analysis of the Constellation requirements for the purpose of determining synergistic and useful RLEP infrastructure emplacement requirements, for example any additional role of RLEP in emplacing the human support communications infrastructure.

4 Glossary and Acronyms

4.1 Glossary

Abort Termination of the nominal mission that allows the crew to be returned to Earth in the portion of the space system used for nominal reentry and touchdown (see Abort to Earth, Abort to Orbit).

Abort to Earth Early mission termination, with direct return to the Earth's surface as the immediate objective.

Abort to Orbit An early mission termination that has an immediate objective of placing a crewed flight system in Earth (or destination vicinity) orbit, prior to return to the Earth's surface.

Annunciate To provide a visual, tactile or audible indication.

Ascent The function of liftoff from the Earth (or mission destination) surface, to spacecraft insertion into Earth/destination orbit.

Automated control Automatic, as opposed to human operation or control of a process, equipment or a system; or the techniques and equipment used to achieve this. Automation is the control or execution of actions with no human interaction. Automated control does not exclude the capability for manual intervention / commanding, but manual intervention / commanding is explicitly not required to accomplish the function.

Autonomous experiments Defined as a flight experiments operating independent of external commands or control (i.e. commands from mission control on Earth). Autonomous experiments can be fully automated or require some degree of manual commanding/intervention.

Autonomous operations Defined as a flight vehicle operating independent of external commands or control (i.e., commands from mission control on Earth). Autonomous operations can be fully automated or require some degree of manual commanding/intervention by the onboard crew. Autonomous operations that do not require onboard crew involvement are, by definition, automated; therefore, the term "autonomous operations" used in the requirements assumes onboard crew involvement in the operations.

Berthing A method of mating two or more Exploration elements in space. During a berthing operation, the two elements are mechanically connected prior to the structural capture and final mating (i.e., one element grapples the other with a robotic arm). One element controls the trajectory and attitude of the other element for the contact and capture. Final mating is generally performed by the berthing mechanism (also see docking).

Cargo Delivery System (CDS) The CDS encompasses the capability to deliver all non-CEV flight elements needed to accomplish human exploration objectives. At such time as CDS elements dock with the CEV, they are part of a human crew occupied system, and are considered part of the CTS.

Cargo Launch Vehicle The Cargo Launch Vehicle is an element of the Cargo Delivery System. The Cargo Launch Vehicle will perform the ascent function for non-crewed elements of the CTS (EDS, LSAM), into an Earth Orbit. Since the Cargo Launch Vehicle will not carry human crew, it will not require Human-Rating.

Catastrophic Hazard A condition that may cause death or permanently disabling injury, major system or facility destruction on the ground, or major systems or vehicle destruction during the mission. (From NPR 8715.3 Safety Manual)

Consumables Resources that are consumed in the course of conducting a given mission. Includes propellant, power, habitability items (e.g., gaseous oxygen), and crew supplies.

Contingency EVA Capability An EVA capability provided to deal with critical failures or circumstances, which are not adequately protected by redundancy or other means.

Crew Exploration Vehicle (CEV) The CEV provides crew habitation and Earth reentry capability for all Exploration Spirals.

Crew Exploration Vehicle Launch Segment (CEVLS) The CEVLS consists of a Crew Exploration Vehicle (CEV), a Crew Launch Vehicle (CLV), and all the dedicated ground support infrastructure necessary to launch the CEV to Earth orbit.

Crew Launch Vehicle (CLV) The CLV is an element of the CTS. The CLV will be human-rated, and will deliver the CEV into a mission-specific Earth Ascent Target Orbit.

Crew Member Human onboard the spacecraft or space system during a mission.

Crew Survival Capabilities designed to keep the crew alive through means such as abort, escape, safe haven, emergency egress, and rescue in response to a Catastrophic Hazard.

Crew Transportation System (CTS) The CTS encompasses the flight elements needed to deliver a human crew from Earth to a mission destination, and return the crew safely to Earth. The CTS must interact with the Ground Support System (GSS) during all Spirals; current architectures require delivery of the EDS and LSAM to Earth orbit through use of the CDS.

Critical Hazard A condition that may cause a severe injury or occupational illness, loss of mission, or major property damage to facilities, systems, or flight hardware.

Day Defined as an Earth day of 24 hours.

Destination Surface System (DSS) The DSS encompasses all elements (exclusive of the surface lander that transports the crew to the destination surface) necessary to enable a long-duration human exploration mission. Examples of DSS elements include a long-duration habitation module, surface power capability, and surface transportation systems. DSS elements will be delivered to the destination surface via the CDS. It is likely that these assets will be pre-deployed in advance of the crew that will utilize them to execute a given Exploration mission.

Destination Surface to Destination Vicinity Phase Starts with the initiation of the ascent (T0) from the destination surface. Representative mission activities include: ascent, abort, and orbit insertion or libration capture. Phase ends after successful destination vicinity insertion/capture.

Destination Vicinity Operations Phase (A) Starts at the successful insertion/capture at the destination vicinity. Representative mission activities include: loiter and phasing, vehicle and system checkout, crew-cargo transfers, undocking and separation. Phase ends at the successful separation of surface lander system for descent burn.

Destination Vicinity Operations Phase (B) Starts after the successful destination orbit insertion or libration point capture, following ascent from destination surface. Representative mission activities include: phasing, vehicle-system checkout, crew-cargo transfer, undocking and separation maneuver, element disposal and/or safing. Phase ends at the completion of the Trans-Earth Injection burn.

Destination Vicinity to Earth Phase Begins with completion of Trans-Earth Injection burn and includes mid-course corrections, cruise to Earth vicinity, element separation and element disposal. Ends with arrival at Earth entry interface or insertion to Earth orbit.

Destination Vicinity to Destination Surface Phase Starts at the initiation of the descent burn from destination vicinity (destination deorbit burn or libration departure burn to destination). Representative mission activities include: descent to destination surface, descent aborts, landing, propulsion system shutdown and safing. For libration architectures, additional activities include orbit capture, phasing, and de-orbit maneuvers. Phase ends when the vehicle has completed all landing activities on the destination surface, including propulsion system shutdown and safing.

Docking A method of mating two or more Exploration elements in space. In a docking operation, the structural mechanisms are brought into contact and captured through independent control of the two vehicles' flight path and attitude. Final mating is generally accomplished by the docking mechanism (also see Berthing).

Earth Ascent Target Orbit The planned orbit, at conclusion of the ascent function.

Earth Departure Stage (EDS) EDS will be used to provide the propulsive force needed to transfer the various flight elements to destination phasing orbits (including the CEV and LSAM).

Earth-Moon Transit Transit of a spacecraft between Earth vicinity and Lunar vicinity in either direction.

Earth Orbit Operations Phase (A) Starts with completion of Earth orbit insertion. Representative activities include: phasing, rendezvous, docking and loiter. Ends with completion of a burn to leave Earth orbit (i.e., Trans-Lunar Injection burn or de-orbit burn).

Earth Orbit to Destination Vicinity Phase Starts after completion of vehicle injection burn (i.e., Trans-Lunar Injection) and includes mid-course corrections, element separation/disposal, and cruise to destination vicinity. Ends with successful insertion/capture at destination vicinity.

Earth to Orbit Phase Starts with liftoff. Representative activities include liftoff through ascent to orbit, ascent crew escape/abort and re-entry/descent during aborts, disposal of elements. Ends with insertion to a stable, 24 hour Earth orbit or return to Earth (in the event of an abort).

Earth Re-entry Phase Begins with arrival at Earth entry interface (for direct re-entry) or completion of Earth orbit injection (for aerocapture), continues through the de-orbit burn and ends with landing on the Earth's surface. Encompasses activities necessary to successfully execute direct-to-Earth aborts during ascent and direct entry return from beyond Earth orbit.

Earth Reference Orbit The orbit designated for assembly of Exploration System elements prior to departure for exploration destinations, defined by the following parameters: Inclination: 28.5-29.0 degrees; Launch Azimuth: 90+/- 5 degrees; Altitude: 307 km - 407 km.

Element A set of functional capabilities necessary to satisfy system-level mission objectives within a given architecture. CTS elements currently include the Crew Exploration Vehicle, Earth Departure Stage, and Lunar Surface Access Module. Elements can perform all system functions within a mission phase, or through mated operations with other exploration elements (as part of a segment).

Emergency Egress Timely and unassisted crew exit of a vehicle (i.e., in response to a Catastrophic Hazard).

Entry footprint Region on Earth's surface defined by the boundaries of the Earth entry corridor for a given vehicle.

Equatorial Region of the Moon Defined as the area between 0-20 degrees lunar latitude (threshold), with an objective of 0-30 degrees **(TBR-7)**.

Escape Removal of crew from the failing spacecraft, due to an imminent catastrophic condition, thus placing them in a safe situation suitable for survivable return to Earth and rescue. Escape includes, but is not limited to, those capabilities that utilize a portion of the original space system for the removal (e.g., escape pods).

Exploration Spiral 1 (Crew Exploration Development and Test) Encompasses the capabilities necessary to insert humans into Earth orbit and return them safely to Earth, employing a post-Space Shuttle flight system. The flight elements of the Exploration Spiral 1 Crew Transportation System are the Crew Exploration Vehicle and Crew Launch Vehicle. Robotic Precursor Missions that are scheduled to launch prior to the Earth orbit demonstration of the Spiral 1 CTS are considered Exploration Spiral 1 missions.

Exploration Spiral 2 (Global Lunar Access for Human Exploration) Encompasses the capabilities necessary to execute human lunar exploration anywhere on the surface of the moon. Lunar global access exploration missions will be 4-7 days in duration on the lunar surface, and do not require pre-deployed surface systems (e.g., Habitation Module or Surface Power). Robotic Precursor Missions scheduled to launch after the Spiral 1 CTS flight demonstration, and prior to the first Spiral 3 Lunar mission are considered Exploration Spiral 2 missions.

Exploration Spiral 3 (Lunar Base and Mars Testbed) Encompasses the capabilities necessary to execute a long-duration human lunar exploration campaign. This campaign requires development of extensive surface systems (e.g., habitation and surface power system). Robotic Precursor Missions that are scheduled to launch after the last Spiral 2 extended- duration lunar mission, and prior to the initial Exploration Spiral 4 mission are considered Exploration Spiral 3 missions.

Extended-Duration (Lunar Mission) Human missions to the lunar surface ranging from 4 days (96 hours) through 7 days. This capability is an objective of Exploration Spiral 2. Extended-duration lunar missions do not require pre-deployed Surface Systems (e.g., habitation modules or surface power system).

Genomics Genetic mapping and DNA sequencing of genes, with applications of the data in medicine or biology.

Geodetic Referenced to the global center of mass of any body (does not refer only to the Earth).

Ground Operations Phase Begins with the start of mission planning. Representative activities include: mission planning, training, receipt of government hardware/software, acceptance, test, checkout, repair, inspection, assembly, integration, servicing and countdown activities. Also includes ground contingency, emergency, abort and turnaround operations. Phase ends with vehicle liftoff.

Ground Support System This system provides all common ground-based capabilities (e.g., mission control, launch-site processing) needed to execute Exploration missions. Facilities and capabilities that are unique to a single Exploration System, such as the CTS, will be included as part of the system it supports.

Guidance and Control The process of directing the movements of a space vehicle, including selection of a flight path and making changes in attitude and speed.

Inclination The angle between the plane of an orbit and the Earth's equator for all geocentric orbits.

In-Space Support System (IS^3) This system will encompass capabilities provided by infrastructure elements (e.g., a communication satellite or network) that are placed in orbital, or lunar/planetary locations. These capabilities are exclusive of those provided by elements of the DSS.

Independent Technical Authority (ITA) A responsibility owned by the NASA Chief Engineer, which is then delegated through the issuance of warrants. A warrant holder is designated as compliance officer over an identified set of engineering and technical requirements or standards.

Integrated Logistics Support (ILS) Is an approach that enables disciplined, unified and iterative management of support considerations into system and equipment design. ILS includes development of support requirements that are related to readiness objectives, to design, and to each other. Requirements in turn drive acquisition of required support; ILS is then employed during the operational phase.

Initial Lunar Phasing Orbit Used in Spiral 2 and 3 to define the orbit where the CEV will assume delta V requirements for a potential docking in lunar orbit. Defined by the following parameters: Altitude: 100 km x 500 km +/**- (TBD-6)** km **(TBR-34)**; Maximum inclination error with respect to the Lunar Reference Orbit; 0.5 degrees **(TBR-28)**.

Launch Availability The likelihood that a given launch will be achieved without a scrub once the mission timeline (first element launch for a multiple launch mission) or the launch countdown call to stations (for a mission scenario involving a single launch) has commenced. Launch availability is composed of four elements: system availability, launch probability, launch site weather constraints and abort weather constraints. Launch Availability can be expressed as: P(LA) = P(SA) x P(LP) x P(LW) x P(AW)

Where:
P(LA) = Launch Availability (overall probability of achieving a launch)
P(SA) = System Availability (probability of hardware being acceptable for launch)
P(LP) = Launch Probability (probability that the vehicle limits are not violated by upper level winds or other natural environment phenomena)
P(LW) = Launch Weather (probability that other launch site weather constraints are not violated)
P(AW) = Abort Weather (probability that abort weather constraints are not violated)

Launch Azimuth The initial heading of a powered vehicle at launch.

Launch Opportunity The period of time during which the relative position of the launch site and orbital plane permit a launch vehicle to perform the ascent function.

Long-Duration (Lunar Mission) Human missions to the lunar surface that require pre-deployed Surface Systems. This capability is a requirement in Exploration Spiral 3, and encompasses surface stays from 42 days (threshold) **(TBR-3)** up to 98 days (objective) **(TBR-70)**.

Low Earth Orbit (LEO) An orbit around the Earth with a minimum orbital altitude of 170 km and is a stable orbit that will not decay rapidly because of atmospheric drag.

Lunar Architecture Focused Trade Study Ongoing engineering analysis (led by NASA JSC) of lunar architecture and mission design options, in support of Exploration architecture decision-making. Results of this study are captured in document ESMD-RQ-0005, “Lunar Architecture Focused Trade Study Final Results”.

Lunar Ascent Orbit Used in Exploration Spirals 2 and 3 to define the orbit that the LSAM must achieve when launching from the lunar surface. Defined by the following parameters: Altitude: 100 km +/**- (TBD-8)** km; Inclination angle (wedge angle) with respect to Lunar Reference Orbit: Maximum of 10 degrees **(TBR-71)**.

Lunar Day The period of time it takes for the Moon to make one complete orbit around the Earth, due to tidal locking. It is marked from a New Moon to the next New Moon. A lunar day is officially 29 days, 12 hours, 44 minutes and 3 seconds long.

Lunar Reference Orbit Used in Exploration Spirals 2 and 3 to define the lunar orbit for rendezvous and docking of Exploration elements. Defined by the following parameters: Altitude: 100 km +/**- (TBD-8)** km; Inclination: Optimized for the mission.

Lunar Surface Access Module (LSAM) Provides crew transport to the lunar surface from the Lunar Reference Orbit and return from the surface to the Lunar Ascent Orbit.

Mating The act of mechanically connecting together two major elements of a system. Mating can be performed in space, through docking or berthing, or on the ground through docking, berthing, or other interfaces.

Mission Refers to the sequence of events that must take place to accomplish prescribed scientific, technological, or engineering objective(s). Includes transportation of a flight system (robotic or human-crewed) to a destination, and operational activities at the destination (e.g., the Martian surface).

Mission Capable Refers to the status of an Exploration flight element or mated elements, which have sufficient consumables to fully execute its intended mission from its current location in space.

Mission Opportunity Refers to the Earth departure window to conduct a mission to another planetary destination such as the Moon or Mars. Typically constrained by orbital mechanics and the design of the Exploration System. If assembly of elements in Earth orbit is required, then "Mission Opportunity" refers to the departure window from Earth orbit based on the capability of the Exploration System.

Mission Phase Definitions Used as the basis for functional flow and decomposition of reference Spiral 3 human exploration mission. The Mission Phases identified were Ground Operations, Earth to Orbit, Earth Orbit Operations, Earth Orbit to Destination Vicinity, Destination Vicinity Operations (A), Destination Vicinity to Surface, Surface Operations, Destination Surface to Destination Vicinity, Destination Vicinity Operations (B), Destination Vicinity to Earth, Earth Reentry, and Recovery (see associated definitions).

Net Habitable Volume The functional pressurized volume left available to the crew after accounting for the loss of volume due to deployed equipment, stowage, trash, and any other items which decrease functional volume. The gravity environment corresponding to the habitable volume must be specified.

Objective Used in requirements language to define the desired capability above the threshold that should be evaluated for feasibility and affordability. Capabilities above the objective are not expected to be pursued or analyzed.

Payload The onboard scientific and exploration utilization (i.e. ISRU) equipment carried by a given spacecraft, generally quantified in terms of mass and volume. Also expressed as the entire mass delivered by a launch vehicle, to orbit.

Polar Regions of the Moon Defined as the area between 80-90 degrees **(TBR-74)** lunar latitude (threshold), with an objective of 70-90 degrees **(TBR-76)**.

Probabilistic Risk Assessment A set of methodologies employed to determine quantitative probability a given end state or states (e.g., Loss of Mission, Loss of Crew) will occur. Probabilistic Risk Assessment results can be used to develop or validate Fault Trees and Failure Modes analysis. They also can be used as a tool for making design and logistics decisions.

Proteomics Analyzing structure, function, and interactions of the proteins produced by the genes of a particular cell, tissue or organism, with applications of the data to medicine or biology.

Proximity Operations Orbital flight operations conducted during any period when two or more vehicles are operating near enough to affect one another (e.g., prior to or post rendezvous and docking).

Recovery Phase Begins with completion of Earth surface landing and includes recovery forces operations, vehicle safing, vehicle configuration for recovery, crew egress, crew return to post-mission facilities. Ends with vehicle recovery to post-mission facilities for refurbishment or disposal.

Regolith Fine-grained powdery layer on the lunar surface above the bedrock.

Remotely Commanded Operations The capability to operate a vehicle, system, or subsystem from an external location (e.g., mission control). Remotely commanded operations do not require the presence of an onboard crew.

Rescue The process of locating the crew, proceeding to their position, providing assistance, and transporting them to an appropriate location.

Robotic Precursor Mission A robotic spacecraft mission that supports The Vision by achieving scientific objectives and/or through preparing for future human exploration activities.

Robotic Precursor Phase Exploration missions accomplished by robotic systems, to prepare for and support future human exploration missions.

Robotic Precursor System Robotic spacecraft that are developed to execute missions that prepare for and support future human exploration, and to accomplish science objectives.

Safety-Critical Software Software is safety-critical if it meets at least one of the following criteria:
1. Resides in a safety-critical system (as determined by a hazard analysis AND at least one of the following:
   a. Causes or contributes to a hazard.
   b. Provides control or mitigation for hazards.
   c. Controls safety-critical functions.
   d. Processes safety-critical commands or data.
   e. Detects and reports, or takes corrective action, if system reaches hazardous state.
   f. Mitigates damage if a hazard occurs.
   g. Resides on the same system (processor) as safety-critical software.
2. Processes data or analyzes trends that lead directly to safety decisions (e.g., determining when to turn power off to a wind tunnel to prevent system destruction.)
3. Provides full or partial verification or validation of safety-critical systems, including hardware or software subsystems.

Segment Used in the CTS requirements development process to express the identity of two or more elements mated together and operating jointly in a given set of mission phases. Segments defined this way facilitate functional decomposition of capabilities throughout the reference Exploration Spiral 3 mission. For example, the In-Space Transportation Segment is comprised of the CEV and an Earth Departure Stage, and comprises the CTS from the Earth Orbit Operations Mission Phase until CEV-EDS separation during the Destination Vicinity Operations Mission Phase. Other segments were defined as the CEV Launch Segment (CEV and CLV operating through separation in Earth orbit), the Destination Transportation Segment (CEV and LSAM operating in the lunar vicinity), and the Earth Return Segment (CEV only, upon separation from LSAM Ascent Stage).

Spiral Development Process A phased system of system development process that allows increasing capabilities to be achieved in support of long range objectives. While work can be accomplished concurrently against the objectives associated with multiple spirals, the completion of all objectives for a given spiral is considered necessary to enable achievement of the succeeding spiral. See associated definitions for Exploration Spirals.

Strategy to Task to Technology Process (STTP) Use of engineering analysis to validate architectural and mission design approaches, and identify technology investment needs.

Surface Operations Phase Starts at the completion of landing on the destination surface, including propulsion system shutdown and safing. Representative mission activities include: science operations, system and operational testing, surface EVA, assembly and maintenance, vehicle checkout, and preparation for ascent. Phase ends at initiation of ascent from the destination surface (i.e., T0).

System A set or arrangement of interdependent elements/segments that are used to accomplish mission objective(s). Exploration systems are Crew Transportation, Cargo Delivery, In-Space Support, Destination Surface, Robotic Precursor System, and Ground Support. These Systems comprise the Exploration System of Systems.

System of Systems A set or arrangement of interdependent systems that are related or connected to provide a given capability. The loss of any portion of the System of Systems will degrade the performance or capabilities of the whole. The systems contained in the Exploration System of Systems (ESS) are: the Crew Transportation System, Cargo Delivery System, In-Space Support System, Destination Surface System, Robotic Precursor System, and Ground Support System. Requirements, constraints, and guidelines that apply to all human and robotic exploration systems are levied against the Exploration System of Systems, and may apply against any or all Exploration Spirals, as specified. The term “System of Systems” is sometimes expressed synonymously as “Super-system”.

Threshold Used in requirements language to define the minimum capability necessary to satisfy the requirement.

Transfer Volume The passageway between two connected element that can contain crew.

Wedge Angle The angle change that must be accomplished (i.e., delta-V capability) to exit an Earth Reference Orbit and achieve a desired Lunar Reference Orbit (see Lunar Reference Orbit).

4.2 Acronyms

AIM	Advanced Integrated Matrix
AO	Announcement of Opportunity
CDS	Cargo Delivery System
CE&R	Concept Exploration and Refinement
CEV	Crew Exploration Vehicle
CEVLS	Crew Exploration Vehicle Launch Segment
CLV	Crew Launch Vehicle
CG	Center of Gravity
CTS	Crew Transportation System

DSN	Deep Space Network
DSS	Destination Surface System
EDS	Earth Departure Stage
EI	Entry Interface
ECLSS	Environmental Control/Life Support System
ESMD	Exploration Systems Mission Directorate
ESS	Exploration System of Systems
EVA	Extra-Vehicular Activity
FOM	Figures-of-Merit
GCR	Galactic Cosmic Ray
GN&C	Guidance, Navigation, and Control
GSS	Ground Support System
HR&T	Human & Robotic Technology
INSTEP	In-Space Technology Experiments Program
IRD	Interface Requirements Document
ILS	Integrated Logistics Support
IS^3	In-Space Support System
ISRU	In-Situ Resource Utilization
ITA	Independent Technical Authority
JIMO	Jupiter Icy Moon Orbiter
KPP	Key Performance Parameters
LAWG	Lunar Architecture Working Group
LEO	Low Earth Orbit
LEPAG	Lunar Exploration Program Working Group
LExSWG	Lunar Exploration Science Working Group
LRL	Lunar Robotic Lander
LRO	Lunar Robotic Orbiter
LSAM	Lunar Surface Access Module
LSI	Landed Surface Interrogator
MEPAG	Mars Exploration Program Analysis Group
NEDD	Natural Environments Definition for Design
NODIS	NASA Online Directives Information System
NP	NASA Publication
NPD	NASA Policy Documents
NPR	NASA Procedural Requirement (Document)
OAG	Operations Advisory Group
ORDT	Objectives and Requirements Definition Team
OSMA	Office of Safety and Mission Assurance
OSP	Orbital Space Plane
PDR	Preliminary Design Review
PDS	Planetary Data System
PRA	Probabilistic Risk Assessment
RFP	Request for Proposals
RLEP	Robotic Lunar Exploration Program
RPS	Robotic Precursor System
SMD	Science Mission Directorate
SPAWG	Space Communications Analysis Working Group

SPE	Solar Particle Event
SRR	System Requirements Review
STD	Standard (Document)
STTP	Strategy to Task to Technology Process (or Panel)
TBD	To Be Determined
TBR	To Be Resolved
TPS	Thermal Protection System
TRL	Technology Readiness Level